

Spectral Characteristics of X-Ray Flashes Compared to Gamma-Ray Bursts

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Abstract. X-ray flashes (XRFs) are a new type of fast transient source observed with the *BeppoSAX* Wide Field Cameras (WFC) at a rate of about four per year. Apart from their large fraction of 2–26 keV X-rays, the bulk properties of these events are similar to those of classical gamma-ray bursts (GRBs). By investigating the wide-band spectra of ten events detected in common with WFC and BATSE, we explore the possibility that XRFs are a low-energy branch of the GRB population. We find that XRF spectra are similar to those of GRBs, and that their low peak energies could be an extension of known GRB properties.

INTRODUCTION

In the study of prompt emission from gamma-ray bursts (GRBs) one is overwhelmed by a large amount of observational data with comparatively little physical understanding. In this realm, one of the keys to better understanding lies in the identification of new, or extreme behavior that differs from that of the bulk ensemble. One such enlightening characteristic would be the identification of the lowest energy bursts, which could help to indicate the limiting form of the radiation emission process.

Most observed GRBs have energy spectra that exhibit νF_ν peak power at energies (E_{peak}) in the range ~ 50 – 300 keV. For example, the distribution of time-averaged E_{peak} for 156 bright bursts measured with *Compton*-BATSE [1] is approximately log-normal, with a centroid of ~ 175 keV and a width of ~ 0.5 decade (FWHM). However, in apparent contradiction to the BATSE results, several bursts with significant X-ray (~ 2 – 10 keV) emission have been observed. In particular, the spectra of several bright bursts measured with *Ginga* suggest that either the distribution of E_{peak} extends below 10 keV, or there is a second (X-ray) spectral component in some bursts [2]. The later hypothesis is supported by the fact that 15% of all BATSE GRBs analyzed show a low-energy excess above the standard continuum model [3].

The most recent observational clue related to the question of low-energy bursts is the discovery [4, 5] of sev-

eral unknown “X-ray Flashes” (XRFs; also referred to as “Fast X-ray Transients”) using the *BeppoSAX* Wide Field Cameras (WFC). These events are distinguished from Galactic transient sources by their isotropic spatial distribution and short (~ 10 – 100 s) durations. Furthermore, they are distinguished from GRBs based on their non-detection above 40 keV with the *BeppoSAX* GRB Monitor — implying larger X/γ ratios than GRBs. In fact, the distribution of X/γ ratio overlaps considerably with that of GRBs. In other respects, such as duration, temporal structure, spectrum (X-ray) and spectral evolution, XRFs exhibit properties that are qualitatively similar to the X-ray properties of GRBs. This similarity led to the suggestion that the XRFs are in fact “X-ray rich” gamma-ray bursts [4, 5].

To investigate the nature of the WFC X-ray flashes, and their true relation to GRBs, untriggered BATSE data were searched, and nine of ten observable flash sources were found to have significant flux above 25 keV (extending in most cases to >100 keV). These data were used to directly compare the *gamma-ray* properties of XRFs to those of the numerous BATSE GRBs [6]. This comparison showed that the flashes are similar in most respects to the long-duration class of GRBs, except that they are significantly softer (based on gamma-ray hardness ratios) and weaker (based on gamma-ray peak flux or fluence) than most long GRBs. In addition, the XRFs appear to be consistent with a low-intensity extrapola-

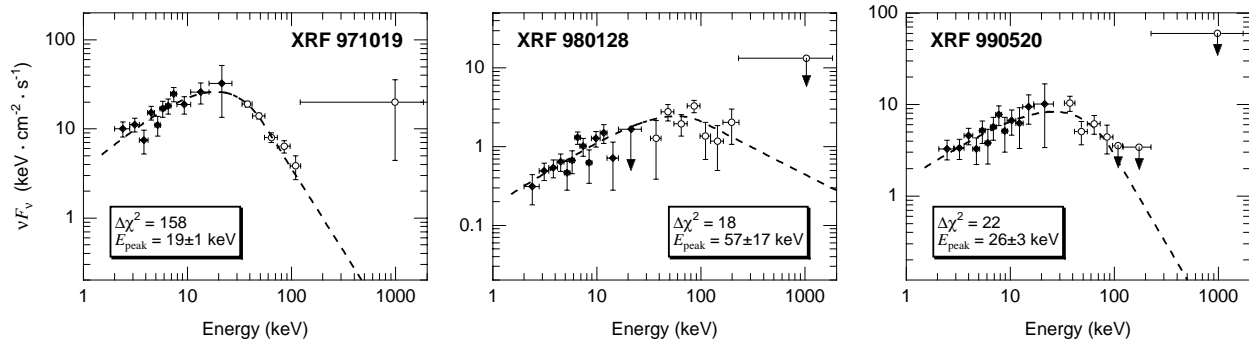


FIGURE 1. Model-dependent deconvolution of spectral data from WFC (*solid diamonds*) and BATSE (*open circles*) for three X-ray flashes. The best-fit Band GRB function is shown as dashed lines. Also indicated are the change in chi-squared ($\Delta\chi^2$) from a single power law to the Band function and the best-fit values of E_{peak} with 1σ errors.

tion of the GRB hardness-intensity (H-I) correlation — suggesting that the flashes could indeed represent a low-energy (or X-ray rich) extension of the GRB population. If XRFs are X-ray rich GRBs, they represent a major fraction ($\sim 30\%$) of the full GRB population.

In this paper, we attempt to further quantify the comparison of X-ray flashes to GRBs by studying wide-band spectral properties. Only by combining WFC X-ray data with BATSE gamma-ray data can spectra with E_{peak} below the gamma-ray regime be parameterized.

JOINT SPECTRAL ANALYSIS

In the 3.8 years when BATSE and WFC were operating nearly simultaneously, a total of 36 GRBs and 17 XRFs were detected with WFC. Due to Earth occultation and data outages, only 18 of the GRB and 10 XRF sources were observable with BATSE. For these events, we have the unique opportunity to study the wide-band energy spectra from 2 keV to $\gtrsim 1$ MeV (depending on brightness). Note that one of the ten XRF sources is not a significant detection in the BATSE data. This event is nonetheless included in the joint spectral analysis because the BATSE data do constrain the wide-band spectrum.

Joint WFC/BATSE spectral analysis has been successfully applied to some of the GRBs. A standard χ^2 fitting technique is used to compare model spectra, folded through the appropriate instrument response functions, to the observed (background-subtracted) counting rates. For example, the time-averaged spectrum of GRB 990510 was found to be well described over 3 decades in energy by the now-standard Band GRB spectral form with $E_{\text{peak}} \approx 143$ keV [7].

Here, the same analysis tools are applied to time-integrated data from each of the XRF sources. The WFC data are from source images obtained by correlating with the WFC coded mask. The approximate energy range

is 2–26 keV. The gamma-ray data are from the BATSE Large Area Detectors (LADs), with 16 energy channels covering the energy range ~ 25 keV to 1.8 MeV. Accumulation time intervals are based on the entire duration of significant emission in the WFC data. The spectrum of each flash was compared to three models: a simple power law (two free parameters), the “Comptonized” model (three free parameters that describe a power law with a high-energy exponential cutoff), and Band’s GRB model (four free parameters describing two smoothly connected power laws) [see, e.g., 1]. The Comptonized (COMP) and Band models describe a curved spectrum that constrains E_{peak} .

All of the flashes are adequately described by either the COMP or Band models, which have average χ^2/ν values of 0.93 and 0.95, respectively. In contrast, the power-law model can be rejected in most cases, with an average $\chi^2/\nu = 1.57$. Based on the change in χ^2 between the single power law and the other models, eight of the ten XRFs show significant evidence ($\Delta\chi^2 > 4$) for a curved spectrum resembling that of GRBs. Examples of spectra for the three brightest XRFs are shown in Figure 1. For these events the curvature is very significant and the Band spectral parameters are well-constrained. For the weaker events the parameters are not as well constrained, particularly the high-energy spectral index in the Band function. This is typical of weak GRBs, where the COMP model is often used in place of the Band function due to low S/N ratio at high energies.

COMPARISON TO GRBS

When comparing spectral parameters between XRFs and GRBs it is important to consider biases due to the way the parameters are measured and how the samples are selected. Unfortunately, we do not have large samples of GRBs measured and selected in exactly the same manner as the XRFs. Hence, we must make the comparisons with

the data that are available. The resulting biases cloud the comparison, as discussed below.

Bright GRBs

The sample of 156 bright, high-fluence BATSE bursts analyzed by Preece et al. [1] represents the best current knowledge of detailed GRB spectral properties. The high signal-to-noise ratio in this sample means that time-averaged parameters are well constrained. In Figure 2, the distributions of E_{peak} and low-energy power-law index α for these bursts are compared to those of the jointly-fit XRFs. The bright-burst distributions are represented by best-fit log-normal functions, which provide good descriptions of the data. Also included are BATSE-only spectral parameters for the 18 WFC-selected GRBs observed with BATSE. These bursts were fit using BATSE LAD data in the energy range ~ 25 keV to 1.8 MeV. In all cases, the spectral model is the Band GRB function. Similar results were obtained using the Comptonized model.

To quantify the comparisons, the K-S test was used to evaluate statistical differences between the WFC-selected samples and the log-normal functions for the bright BATSE GRBs. The results are that XRFs have significantly lower values of E_{peak} than the bright BATSE GRBs, with K-S probability $P_{\text{KS}} = 1.5 \times 10^{-8}$, while the WFC-selected GRBs have E_{peak} 's that are consistent with those of the bright BATSE bursts. This latter agreement is not surprising since most of the WFC GRBs are rather bright. It does, however, indicate that (at least for bright bursts) biases due to different sample selections are small. Biases due to the fact that the XRFs were fit over a different energy range (and using different instrument data) than the GRBs remain unquantified.

The α distributions of WFC XRFs and WFC-selected GRBs are each statistically consistent with that of bright BATSE bursts, with $P_{\text{KS}} = 0.11$ and 0.32 , respectively. Detailed comparison of the high-energy power-law index β is problematic because it is not well constrained for many of the XRFs. However, the mean value for the four brightest flashes is $\langle \beta \rangle \approx -2.5 \pm 0.5$, which is consistent with the average of -2.1 obtained for bright GRBs. Thus, excluding the potential measurement biases mentioned above, it appears that the main outstanding spectral difference between GRBs and XRFs is that XRFs have lower E_{peak} values, on average.

Dim GRBs

Another significant bias that must be considered is the fact that weak bursts have different spectral properties than bright bursts [see, e.g., 8, 9]. In particular, there is

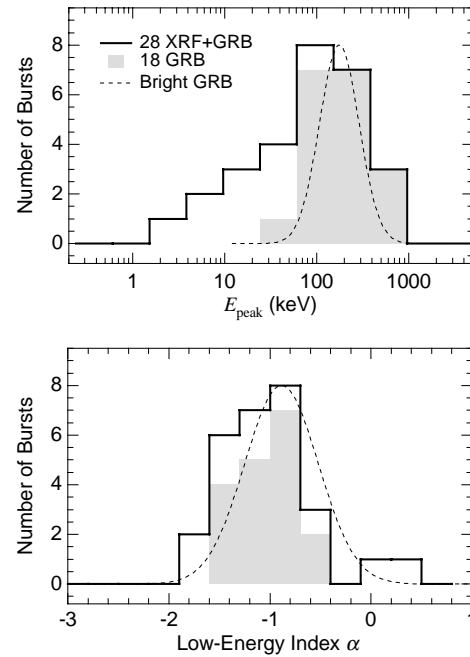


FIGURE 2. Jointly fit time-averaged spectral parameters of XRFs compared to BATSE-only parameters of GRBs. Dashed curves are log-normal fits to parameters from 156 bright GRBs [1], normalized to the peaks of the XRF+GRB histograms.

a strong correlation between E_{peak} and peak GRB flux (measured in the 50–300 keV energy range). Thus, if XRFs are related to GRBs, we expect them to have lower E_{peak} , on average.

For a detailed comparison with weak (and bright) GRBs, we use the spectral catalog of Mallozzi et al. [10], which contains model fit parameters for 1,275 BATSE bursts (obtained with LAD data). Although the catalog contains spectral parameters for several spectral models, we employ the COMP model, which is more robust for fitting weak bursts with few high-energy counts. In practice, the spectral parameters derived from COMP and Band model fits are similar [10].

Figure 3 shows distributions of E_{peak} versus duration (T_{50}), power-law index (α) and peak flux (P_{1024} , evaluated on the 1.024 s timescale in the energy range 50–300 keV) for the XRFs and BATSE GRBs. Since the XRFs have (gamma-ray) durations comparable with long GRBs, the Mallozzi et al. catalog has been selected for long bursts with $T_{50} > 1$ s and that have standard peak fluxes and fluences available. This results in a sample of 802 long GRBs that are used for comparison in the two right-most plots in Figure 3.

The plot of E_{peak} versus peak flux is particularly informative since it shows how the XRFs compare with the long GRB H-I relation. For this sample of GRBs, the correlation is very significant, with a Spearman rank or-

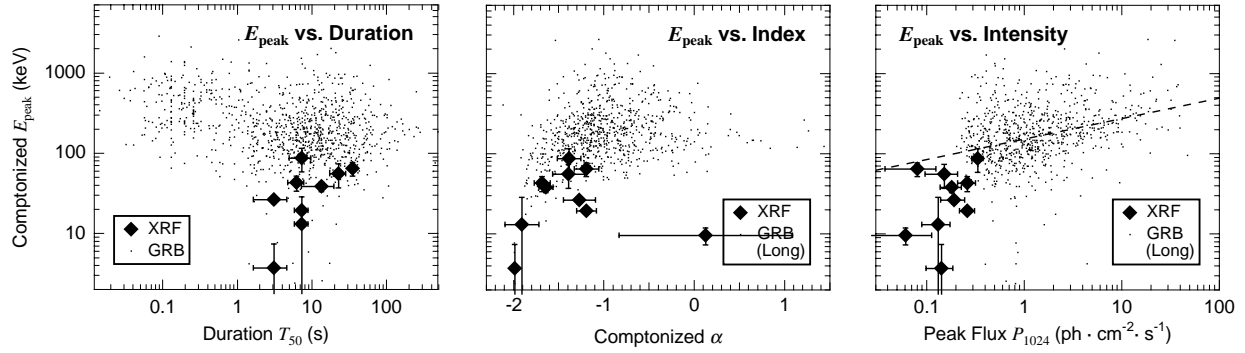


FIGURE 3. Jointly fit time-averaged spectral parameters of XRFs compared to BATSE-only [10] parameters of GRBs. Measurement errors for the GRBs are excluded from the plots for clarity. The dashed line at right indicates the best-fit power law to the GRB distribution.

der probability of 5.5×10^{-16} . At the extremes of the distribution are the bright GRBs corresponding to the Preece et al. sample, with $P_{1024} > 10 \text{ ph} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$ and $\langle E_{\text{peak}} \rangle \sim 350 \text{ keV}$, and the weakest GRBs near the BATSE trigger threshold with $\langle E_{\text{peak}} \rangle \sim 100 \text{ keV}$.

Statistically, the XRFs are inconsistent even with the weakest 5% of GRBs ($P_{1024} < 0.3$), with a two-distribution K-S probability of $P_{\text{KS}} \approx 10^{-5}$. However, the average XRF flux of $P_{1024} = 0.16$ is nearly factor of two below that of the weakest BATSE bursts.

Assuming the H-I correlation extrapolates unchanged below the BATSE threshold with a simple power law (see Figure 3), the expected mean and (log-normal) standard deviation of E_{peak} at the average XRF flux level are 94 keV and 0.25 decades, respectively. The XRFs are marginally inconsistent with this extrapolation, with $P_{\text{KS}} \approx 10^{-4}$.

CONCLUSION

We have shown that X-ray flashes have significantly curved time-averaged energy spectra that are quantitatively similar to those of gamma-ray bursts. The main difference is that XRFs have peak power at significantly lower energies than most GRBs. Combined with our previous work, this lends further support to the idea that XRFs could be a low-energy extension of the GRB population.

We also find that, statistically speaking, XRFs are marginally inconsistent with a power-law extrapolation of the GRB hardness-intensity distribution. However, given the considerable systematic uncertainties in this extrapolation, the marginal statistical inconsistency is not a strong argument to rule out a GRB/XRF association. It is also important to note the two key biases in this comparison: Firstly, the observed XRFs are purely X-ray selected, so they probably have lower E_{peak} than average. Secondly, the XRF spectra were fit using X-ray and

gamma-ray data, whereas the GRBs used only gamma-ray data, so E_{peak} for weak GRBs could be overestimated. With these considerations, it is not unreasonable to conclude that XRFs are indeed low-energy, or X-ray rich GRBs.

Final conclusion of this problem will undoubtedly require more *wide-band* XRF measurements. Continued XRF observations with HETE-II and *BeppoSAX* may be sufficient, but it will be difficult to compare these data to known GRBs since they lack high-sensitivity gamma-ray measurements.

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